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NRQCD Prediction for the Polarization of the J/ψ Produced from b-decay

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Presented at the Meeting of the Division of Particles and Fields, August 1996, in Minneapolis. The work presented here is based upon a recent paper[a] done in collaboration with Oscar F. Hernández, Ivan Maksymyk, and Hélène Nadeau. The NRQCD predictions for the polarization of the J/ψ produced in $b \to J/\psi + X$, as well as the helicity-summed production rate are presented.

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A rigorous theoretical framework within which quarkonium production can be studied is provided by the NRQCD factorization formalism[1]. This approach is based on NRQCD, an effective field theory that that can be made equivalent to full QCD to any desired order in the heavy-quark velocity v. The NRQCD Lagrangian is

$$\begin{aligned}\mathcal{L} &= -\frac{1}{2}\mathrm{tr}\, G_{\mu\nu}G^{\mu\nu} \;+\; \sum \bar{\Psi}_\ell \, i\not{D}\Psi_\ell \\ &\quad + \psi^\dagger \left(iD_0 + \frac{\mathbf{D}^2}{2m_Q} \right)\psi \;+\; \chi^\dagger \left(iD_0 - \frac{\mathbf{D}^2}{2m_Q} \right)\chi \;+\; \cdots \qquad (1)\end{aligned}$$

where $G_{\mu\nu}$ is the gluon field-strength tensor, Ψ_ℓ is the Dirac spinor field for a light quark, $D^\mu = \partial^\mu + igA^\mu$ is the gauge-covariant derivative (with g being the QCD coupling constant), m_Q is the heavy quark mass, and ψ and χ are 2-component fields that annihilate heavy quarks and create heavy antiquarks respectively. Color and spin indices on the fields have been suppressed. Eq. 1 describes a fully relativistic field theory for the light degrees of freedom coupled with a Schrödinger field theory for the heavy quarks and antiquarks. The relativistic effects of full QCD are reproduced through additional terms represented by the $\cdots$ in Eq. 1. In principle there are infinitely many terms. However, using NRQCD v-scaling rules it is possible to retain only those that contribute through a given order in v.

The NRQCD factorization formalism is a rigorous derivation within NRQCD of a factored form for quarkonium production and decay rates. A central result

is that inclusive quarkonium production cross sections must have the form

$$\sigma(A+B\to H+X)=\sum_n \frac{F_n}{m_Q^{d_n-4}}\langle\mathcal{O}_n^H\rangle \ , \tag{2}$$

where the $\mathcal{O}_n^H$ represent NRQCD four-fermion production operators, with the index n labeling color and angular-momentum quantum numbers. The NRQCD matrix elements $\langle\mathcal{O}_n^H\rangle \equiv \langle 0|\mathcal{O}_n^H|0\rangle$, parameterize the hadronization of a heavy-quark-antiquark pair with quantum numbers n into a quarkonium state H. They scale as the parameter v raised to a power. The short-distance coefficients F_n are obtainable in perturbation theory as a series in $\alpha_s(m_Q)$. Information on the order in v of the matrix elements, along with the dependence of the F_n on coupling constants, permits us to decide which terms must be retained in expressions for observables to reach a given level of accuracy.

Consider the specific case of J/ψ production. In many instances the most important NRQCD matrix elements are $\langle\mathcal{O}_1^\psi({}^3S_1)\rangle$, $\langle\mathcal{O}_8^\psi({}^3S_1)\rangle$, $\langle\mathcal{O}_8^\psi({}^1S_0)\rangle$, and $\langle\mathcal{O}_8^\psi({}^3P_J)\rangle$. Inclusive production of J/ψ from b-decay provides two measurable combinations of these matrix elements. The first one is the helicity-summed rate $\Gamma(b\to J/\psi+X)$. The second combination concerns the polarization parameter α appearing in the electromagnetic decay rate of J/ψ to lepton pairs:

$$\frac{d\Gamma}{d\cos\theta}\big(\psi\to\mu^+\mu^-(\theta)\big)\propto 1+\alpha\cos^2\theta \ , \tag{3}$$

where the polar angle θ is defined in the J/ψ rest frame for which the z-axis is aligned with the direction of motion of the J/ψ in the lab.

The branching ratio for $b\to J/\psi+X$ is calculated using a matching procedure [2]. One obtains [3]

$$\begin{aligned} &BR(b\to J/\psi+X)= \\ &\quad 0.002\big\langle\mathcal{O}_1^\psi({}^3S_1)\big\rangle+0.1\big\langle\mathcal{O}_8^\psi({}^3S_1)\big\rangle+0.2\big\langle\mathcal{O}_8^\psi({}^1S_0)\big\rangle+0.6\frac{\big\langle\mathcal{O}_8^\psi({}^3P_0)\big\rangle}{m_c^2} \ . \end{aligned} \tag{4}$$

Only the leading color-singlet piece and the leading color-octet pieces in the relativistic v^2-expansion are considered. The above formula concurs with previous results [4].

According to the NRQCD v-scaling rules, the color-octet matrix elements in Eq. 4 are all expected to be suppressed by v^4 with respect to $\langle\mathcal{O}_1^\psi({}^3S_1)\rangle$. However the short-distance coefficients in the color-octet terms are some 50 times larger than the color-singlet coefficient!

Beneke and Rothstein[5] and Braaten and Chen[6] have developed techniques for deriving the production rates of quarkonia with specified helicities. Applying their methods one obtains an expression for the polarization parameter[3]

$$\alpha = \frac{-0.39\langle\mathcal{O}_1^\psi(^3S_1)\rangle - 17\langle\mathcal{O}_8^\psi(^3S_1)\rangle + 52\langle\mathcal{O}_8^\psi(^3P_0)\rangle/m_c^2}{\langle\mathcal{O}_1^\psi(^3S_1)\rangle + 44\langle\mathcal{O}_8^\psi(^3S_1)\rangle + 61\langle\mathcal{O}_8^\psi(^1S_0)\rangle + 211\langle\mathcal{O}_8^\psi(^3P_0)\rangle/m_c^2}\,. \qquad (5)$$

While experimental determinations of helicity-summed $BR(b \to J/\psi + X)$ have already been carried out[7], a measurement of the polarization parameter α is not yet available. Anticipating the availability of this latter measurement, it is interesting to determine the range of α which is consistent with existing information on the matrix elements $\langle\mathcal{O}_1^\psi(^3S_1)\rangle$, $\langle\mathcal{O}_8^\psi(^3S_1)\rangle$, $\langle\mathcal{O}_8^\psi(^1S_0)\rangle$, and $\langle\mathcal{O}_8^\psi(^3P_0)\rangle/m_c^2$, and with various constraints on linear combinations of these quantities[8]. The *maximum* value for α is -0.09, and the *minimum* value for α is -0.33.

Unfortunately, due to the large number of poorly determined parameters the expected range of α as predicted by NRQCD is large. It may be that an accurate NRQCD prediction of the polarization parameter (beyond leading order) will not be possible for a long time. This possibility, however, does not degrade the importance of this calculation, since an experimental determination of α — in conjunction with these results — will most certainly serve to tighten the constraints on the possible values of the color-octet matrix elements. In fact, the NRQCD prediction for α is very sensitive to the values of the color-octet matrix elements. This offers the hope that a measurement of the polarization of J/ψ produced in $b \to J/\psi + X$ will be instrumental in determining $\langle\mathcal{O}_8^\psi(^3S_1)\rangle$, $\langle\mathcal{O}_8^\psi(^1S_0)\rangle$, and $\langle\mathcal{O}_8^\psi(^3P_0)\rangle$.

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